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Modelling vertical profile of water vapour density in tropical environment

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Abstract : A mathematical model of ρ, the atmospheric water vapour density, based on radiosonde data in Indian tropical climate has been presented. The vertical profile of it is linear within the lower height range but above 1–2 km height, it follows an exponential curve similar to the gradient of radio refractivity profile. As a ready-reckoner, this model would be very helpful for millimeter wave designing in tropical environment

Keywords : Millimeter wave attenuation, radio refractivity, atmospheric water vapour density, radiosonde

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1. Introduction

A number of studies have been performed on scattering and scintillation effects of radio and radar propagations resulting from the turbulent refractive structure of atmospheric boundary layer and on its temporal and spatial distributions and are recognised for decades [1,2]. Dependence of the refractivity on temperature and relative humidity is very important. It has great impact in using millimetric and submillimetric waves for radio communication in the tropics and in the problem of radio attenuation which of late has grown in importance [3,4]. In millimetric wave band resonant absorption occurs at the wavelength of 13.5, 1.5 and 0.75 mm for water vapour and at 5.0 and 2.5 mm for oxygen. This absorption is nearly constant for oxygen; but for the atmospheric water vapour density, ρ, due to diurnal variation of the humidity, rapidly decreases with height h. It is 50% at about 1.5 km while at the upper boundary it may be around 0.1% of what it is at the Earth's surface.

Over a hot tropical climate with high humidity content, specially in the coastal region, variation of surface refractivity N_s and its gradient value ΔN are very high. At high temperature, dry part of N_s is either comparable or less than its wet part which often determines the refractivity condition of the atmosphere. The aim of this paper is to establish a model for vertical profile of ρ over first 1 km of the Indian tropical region and to correlate them with ΔN. Variations of ρ with h have been computed and can be shown that it has a high positive correlation with ΔN. The parametric values used in this model show strong dependence on location of the station but almost independent of seasonal variation.

2. Atmospheric water vapour density profile

Due to its role in causing attenuations at frequencies above 15 GHz, atmospheric water vapour distribution in the tropics seems to have great significance in producing large refractivity gradient that leads to anomalous propagation condition. Using data obtained through daily balloon flights conducted by the India Meteorology Department (IMD) several studies [5,6] on radioclimatology over the Indian sub-continent were performed, but they ignored the existence of low level intermediate layers. Frequent occurrence of the intermediate layers produces significant effects on tropospheric radiowave propagation [2]. This study is based on the radiosonde data obtained from IMD, Dum Dum for 2 consecutive years from 7 different meteorological stations spread over the coastal region (Calcutta, Madras and Port Blair) and on inland region (Gauhati, Delhi, Nagpur and Jodhpur). We have calculated monthly variation of ρ for the surface level and 900 mb level (which is vertically 1 km up from the Earth's surface) and found the ρ-profiles at these two levels of Calcutta to be almost identical. Also during the monsoon and winter months of 1986, ρ of this coastal region attained the maximum and minimum values typically around 16 and 3.5 gm.m^{-3} respectively.

One of the main cause of radar returns from clear air is the presence of inhomogeneties in radio refractive index (RRI) resulting from the turbulence. In the direction of propagating waves, decrease in N with h produces bending of rays that are restricted within a vertical plane primarily. In commonly used microwave bands N can be expressed [7] as

$$N = 77.6\ P/T + 3.73 \times 10^5\ e/T^2, \tag{1}$$

where P, e and T are total atmospheric pressure (mbar), water vapour pressure (mbar) and dry bulb temperature (°K).

With the following conditions, Bean and Dutton [1] established the 3-part refractivity model of the atmosphere which has been widely utilised to explain point-to-point radio relaying over distances upto several km, where N decreases with h (in km above msl) in the following manners :

(i) form the Earth's surface h_s based on the effective Earth's radius concept over horizontal distances upto 160 km,

$$N(h) = N_s + \left(h - h_s\right) \cdot \Delta N; \quad h_s \le h \le \left(h_s + 1\right), \tag{2}$$

ΔN is initial radio refractivity gradient in first 1 km height;

(ii) exponentially from $(h_s + 1)$ to 9 km with a minimum value of 105; and

(iii) exponentially assuming from the vertical height above 9 km where less than 10% of the total bending occurs for rays having small elevation angle θ_0.

Nature of the vertical variation of ρ (gm/m^3) *vs* h (km) over Indian tropical regions is shown in Figure 1 and is found similar to that of standard vertical *N*-profile with 3 distinct

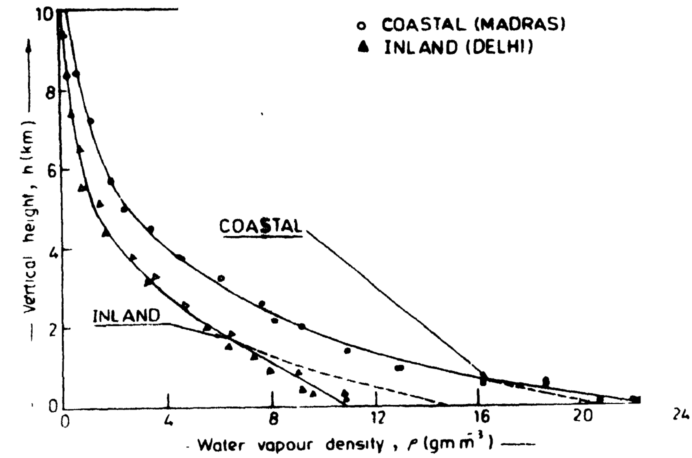

Figure 1. Vertical profile of the water vapour density in tropical climate for the month of May.

parts in the model atmosphere. These curves (with about 20 data points for each station) are not equally smooth from the top height of 10 km to ground level. Lower part of ρ-profile shows a linear decrease within 0–2 km with correlation coefficient r around 0.94, while the middle part shows an exponential decrease within 1–10 km according to parametric values given in Table 1. Higher parts (above 10 km) are insignificant with values almost zero ($\simeq$ 0.1–0.2 gm/m^3).

Table 1. Variation in parametric values of ρ *vs* h curve fitting.

Station	Linear (0–1 km) $\rho = \alpha + \beta h$		Exponential (1–10 km) $\rho = A \exp(Bh)$	
	α	β	A	B
Inland (New Delhi)	10.80	- 0.0028	14.75	- 0.0004923
Coastal (Madras)	22.78	-0 0100	20.94	- 0.0004166

Compared to the coastal station, the vertical profile for inland station shows sharp increase of ρ near the ground surface. There are change-over/break points, indicated by arrows, around 1.8 km and 0.8 km for the inland station, Delhi and coastal station, Madras respectively (Figure 1). Below the break-point almost all ρ values follow a least square straight line path (solid line) but above that the least square fitting is an exponential curve. As possible extensions for each of the exponential curves, respective break points were joined from ground surface by dotted lines. Beneath these break points exponential curve fitting falls below straight line fitting curve for coastal region and is strikingly reversed for inland region. Obviously, depending on the exact location of Indian tropical stations, locus of the break points would provide very useful data for microwave and millimeter wave link design.

3. Refractivity modelling with water vapour pressure gradient

The temporal variations of integrated water vapour content, in Indian tropical region, were correlated with the temporal variations of ρ at different h with maximum value of r occurring around 2 km height and decreasing on either side of that [8]. Above 10 km, it is insignificant. Evans and Hagfors [4] showed theoretically that water vapour contribution above 10 km towards microwave or millimeter wave attenuation was only 1% of the total value. As most of the microwave link usually propagates within 0.5–2.5 km height, it seems to be adequate to measure ρ at that significant range for obtaining a clear picture of the temporal variation of integrated water vapour and to locate the break-points.

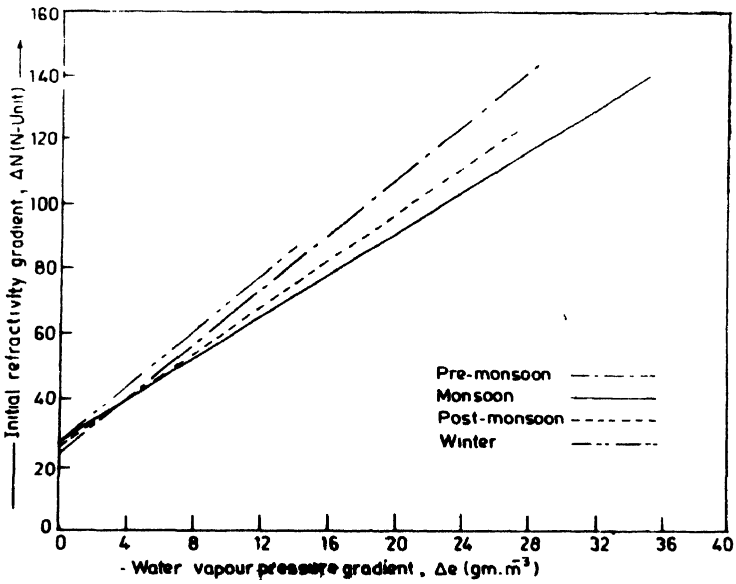

Figure 2. ΔN *vs* Δe plot for the first 1 km height range showing seasonal dependence in coastal station at Calcutta.

In most of the western countries, in average condition within first 1 km of atmosphere above the Earth's surface, there exists a good relation between ΔN and N_s and the least square estimation of the above relation gives the well known expression [1]

$$-\Delta N = 7.32 \exp\left(55.77 \times 10^{-4} N_s\right) \quad (3)$$

with the value of r, 0.6–0.93. But depending on the location of meteorological stations in Indian tropical region, corresponding r is found to vary from 0.30–0.50 only, indicating the inadequacy of the above relation. A better linear relationship can be established with differential refractivity ΔN and differential water vapour pressure Δe. The ΔN as calculated from surface to 900 mb level and its seasonal variation with Δe over 0–1 km height range for Calcutta were plotted in Figure 2. A model of ΔN for this coastal station formulated using 2 years IMD radiosonde data is found to have a linear relationship with Δe,

$$\Delta N = a + b.\Delta e \tag{4}$$

where a, b are constants for model parameters, and their seasonal variations (least square fitting) have been calculated. In all the seasons ΔN has been found to be highly correlated with Δe and there exists some seasonal dependence, as b, the gradient of the linear-fit has its minimum and maximum value in monsoon and winter months respectively. Still the linear

Table 2. Linear fitting of ΔN *vs* Δe in Calcutta (seasonal) [$\Delta N = a + b.\ \Delta e$].

Season	a	b	r
Winter	26.97	4.36	0.975
Premonsoon	24.58	4.22	0.990
Monsoon	27.76	3.22	0.996
Postmonsoon	26.70	3.62	0.980

fitting curve for the months of premonsoon and winter are almost parallel and have higher b-values. Occurrences of thunderstorm and nor'westers in this coastal region in postmonsoon season may result in lowering of the b-values. Table 2 shows the constants and also values of r in different seasons.

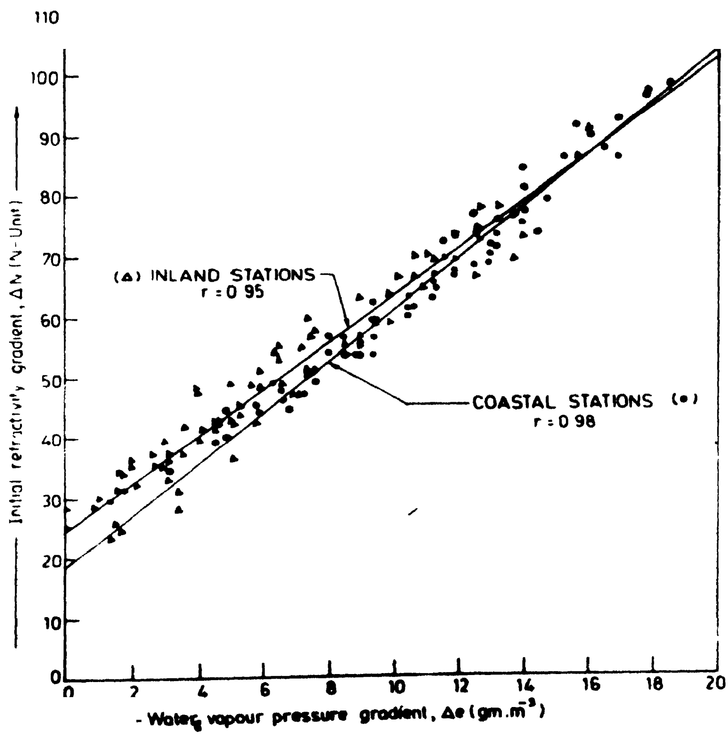

Figure 3. ΔN *vs* Δe relationship for the Indian coastal and inland stations.

As May is the month preceding monsoon, relative humidity (RH) would be maximum and so appreciable variation in ΔN with Δe within 1 km height observed. Figure 3 shows the least square estimation of variations as they occurred in Indian coastal and inland stations (shown with o and Δ respectively) and were found to be well-correlated with the values of $r = 0.98$ and 0.95 for those stations respectively. As observed, both from Figures 1 and 3 and

Table 3. Linear fitting of ΔN *vs* Δe for Indian stations in May [$\Delta N = a + b.\Delta e$].

Stations	a	b	r
Coastal	18.61	4.31	0.98
Inland	24.12	3.96	0.95

also from Table 3, the linear fitting for coastal stations have higher value of b than that of the inland stations.

4. Role of water vapour in attenuating high frequency signals

The water vapour, perhaps one of the major lower atmospheric constituents, often controls basic atmospheric processes including the weather phenomena. Effects of the atmosphere have been paradoxically a boon and a hindrance for the development of the near millimeter wave technology. This spectral range was handicapped for a long time owing to the formidable development problems, and also due to atmospheric attenuation which is remarkably higher at long wavelenghts. Because of its role in modifying the turbulence related refractivity fluctuations the water vapour distribution, especially in tropics, assumes great significance and causes attenuation at frequencies of about 15 GHz to produce large variation in refractivity leading to the anomalous propagation conditions. Expanding requirement for using SHF and EHF bands in terrestrial radio systems and satellite communications, specially in tropical and subtropical regions, demand *a-priori* knowledge of water vapour distributions and rain rate statistics in optimising the performances.

Molecular absorption is primarily caused by water vapour and oxygen in several GHz to hundred GHz [9]. While absorption by oxygen has an invariant parameter which can be accounted for and which does not change with latitude or season, that for water vapour is highly variant. As was suggested by Croom [3], water vapour molecules interact with the incident electromagnetic radiation producing rotational excitations at 22.235, 183.311 and 324 GHz. However, attenuation due to water vapour becomes serious only beyond 15 GHz and hence attenuation for rain is much more important for the incoming system and is to be used in tropical and subtropical regions. The University of Texas and Bell Telephone Laboratories have drawn water vapour absorption curves as a function of water vapour concentration over the paths between mountain peaks in Colorado with elevations ranging from 3.66 to 4.27 km. Results of such observations have been shown in Table 4 below.

Millimeter wave system is attractive for its ability to penetrate somewhat opaque atmosphere (like haze, drizzle, fog, smoke, dust and cloud) under the circumstances where

Table 4. Signal attenuation in different millimeter wavelength

Wavelength in mm	Attenuation (dB/km) for	
	Water Vapour (1 gm/m^3)	Oxygen
8.60	0.06	–
4.30	0.10	0.22
2.15	0.12	–

optoelectronics and infrared systems fail. An in-depth knowledge on the properties of atmospheric transmission is required to evaluate the advantage of millimeter wave over shorter wavelength. Theoretical calculation on microwave and millimeter wave attenuation coefficient, α for such exponential height distributions of water vapour in a model atmosphere was performed. Because of low water vapour content, the attenuation due to it decreases with the increasing height from ground surface [4].

Introduced by water vapour molecules for 94 GHz millimeter wave link in this tropical region, α was evaluated here (Figure 4) by using the expression deduced by Croom [3]. The

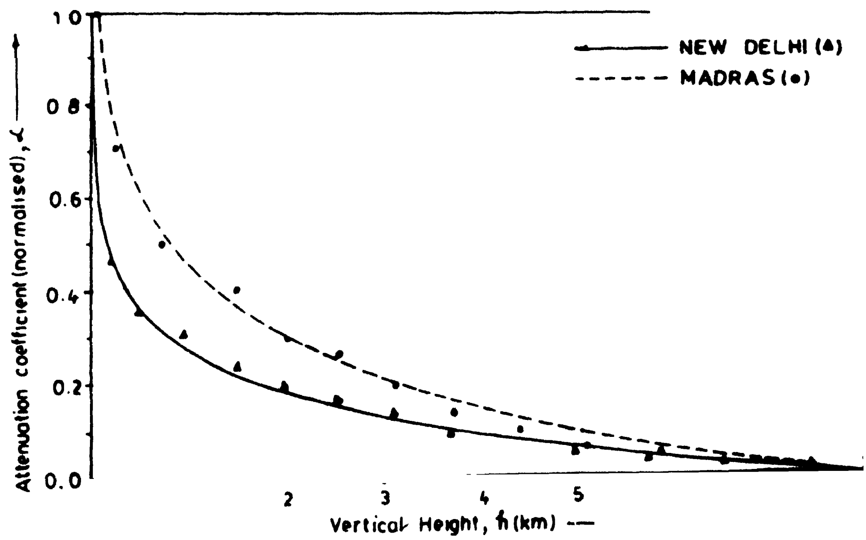

Figure 4. Variation in normalised attenuation α with height h.

attenuation curves for the inland station, New Delhi and the coastal station, Madras follow almost identical nature of variation. The height, h in km for those centres can be presented by the expressions,

$$
\begin{aligned}
h &= 7.778 \exp(-4.525\,\alpha) \quad \text{for Madras and} \\
h &= 8.018 \exp(-7.638\,\alpha) \quad \text{for New Delhi.}
\end{aligned} \tag{5}
$$

5. Conclusion

With the increasing interest in millimeter and submillimeter waves, there is a need for a reliable model in predicting average loss and delay effects from easy-to-obtain meteorological data. Such model would find considerable practical applications in conversion of the basic climatological variables (temperature, relative humidity and pressure) into transfer characteristics of a path. These data and variation in water vapour density within the first few kilometers above the surface at inland and coastal regions in India should be useful for estimation of atmospheric absorption in the propagation paths of microwave and millimeter-wave communication.

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